Complex Networks/
Foundations of
Information Systems

6 March 2013

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1. REPORT DATE
06 MAR 2013

2. REPORT TYPE

3. DATES COVERED
00-00-2013 to 00-00-2013

4. TITLE AND SUBTITLE
Complex Networks/Foundations of Information Systems

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHOR(S)

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Office of Scientific Research, AFOSR/RTC, 875 N. Randolph, Arlington, VA, 22203

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Presented at the AFOSR Spring Review 2013, 4-8 March, Arlington, VA.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:
   a. REPORT unclassified
   b. ABSTRACT unclassified
   c. THIS PAGE unclassified

17. LIMITATION OF ABSTRACT
   Same as Report (SAR)

18. NUMBER OF PAGES
   29

19a. NAME OF RESPONSIBLE PERSON

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18
NAME: Complex Networks/Foundations of Information Systems

BRIEF DESCRIPTION OF PORTFOLIO:

Complex Networks and Foundations of Information Systems uses measured information to assure, manage, predict, and design distributed networks, systems, and architectures

LIST SUB-AREAS IN PORTFOLIO:

- *Local Network Research*: Guarantee and assure information transmission
- *Network Management Research*: Network and system protocols for resilient and robust
- *Global Network Research*: Mathematically represent network performance and design robustness
- *Foundations of Information Systems Research*: Measure, predict, and verify information system properties
Goals:

- **Measure** system performance and **calculate risk**

- **Preserve critical information structure** and minimize latency over a heterogeneous distributed network and system

- **Ensure network and system robustness and resilience** under a diverse set of resource constraints and manage using dynamic models

- Represent global properties of a networked system in a **unified mathematical framework** for architecture and design

- **Assess and Predict** heterogeneous distributed systems performance using unified mathematical framework

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**Foundations Goals**

**Complex Networks Goals**
Payoffs:

• Preserve critical information structure in a network rather than just delivering packets or bits

• Quantify likelihood of a given network management policy to support critical mission functions

• Predict and manage network and system failure comprehensively

• Assess and verify properties of a distributed heterogeneous system where there is limited access to its elements

• Assess dynamic Air Force system mission performance and assess risk of failure
Complex Networks and Information Systems uses measured information to assure, manage, predict, and design distributed networks, systems, and architectures.
Information Systems Measurement

We wish to understand what and how to measure systems for representations that are traceable to mission performance and have quantifiable risk

What to measure?

How to measure?
Approach: Techniques on what and how to measure on any software, network, and hardware integrated system with probabilistic model checking.

Payoff: Large system state spaces can be verified and risk calculated in a computationally efficient way.
Approach: There are many different ways to represent networked systems. There needs to be a principled way of selecting the best inputs for geometric models to parameterize system performance.

Payoff: Systems can be parameterized in such a way as to minimize computational overhead and inaccuracies in model prediction using sparse geometric graph theory.
Approach: Sample large systems guided by understanding of geometric invariants and risk analysis in how measurements were constructed. Payoff: Minimum risk can be incurred from measurements of large system while still sampling in most computationally efficient way.

### Minimum Risk Outcome for Graph Sampling

<table>
<thead>
<tr>
<th>The Underlying Network-Graph</th>
<th>The Inferred Network-Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G = (V, E)$</td>
<td>$\hat{G} = (V, \hat{E})$</td>
</tr>
<tr>
<td>Underlying Graph Characteristic</td>
<td>Inferred Graph Characteristic</td>
</tr>
<tr>
<td>$\eta(G)$</td>
<td>$\eta(\hat{G})$</td>
</tr>
</tbody>
</table>

- Let $G$ be a connected, undirected binary graph
- Express the relationship between $G = G_{true}$ and $\hat{G} = G_{observed}$, in terms of their $n \times n$ adjacency matrices, as

\[
W_{observed} = W_{true} + W_{noise}
\]

where $W_{noise}$ captures Type I and Type II errors.

- **Our Goal:** Construct an estimator $\hat{W}$ of $W_{true}$ from $W_{observed}$ for which

\[
\|f(\hat{W}) - f(W_{true})\| < < \|f(W_{observed}) - f(W_{true})\|
\]

for any smooth statistic $f(W)$.

### Geometric Strategies for Sampling Graph

- **Matrix Geodesics ($\alpha \in [0, 1]$)**
  
  1. **Euclidean geodesic:** $\gamma(\alpha) = \alpha A + (\alpha - 1)B$.
  2. **Log-Euclidean geodesic:** $\gamma(\alpha) = \exp(\alpha A + (1 - \alpha)B)$.

### Risk Performance Peer to Peer Network Data
• We wish to characterize network and system performance from measurement and develop coding, protocol, and architectures that adapt according to network/system state.
Approach: Develop a taxonomy of network properties through curvature and timescale invariants from hyperbolic geometry

Payoff: Space of network models can be developed and design principles and analysis algorithms derived to predict network behavior

Geometric Curvature Invariant

1. 3-point “Triangle test” - Are triangles universally δ-thin?
   - Select triangles
   - For each triangle note shortest side $L$ and computed the $\delta$
   - Counted number of such triangles, indexed by $\delta$ and $L$

Network Taxonomy

Taxonomy of Physical Architecture Across Networks

Characterization of Network Stack Across Layers (curvature connected to congestions)

Application

Social Network

Protocol

Peer to Peer

Architecture

IP Layer

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Entropy Classes for Dynamic Network Models
Lizhong Zheng, MIT

Approach: Deriving models for network protocol analysis has assumed fixed protocols without the benefit of feedback or dynamic correlations in coding and protocol. Using Renyi correlation analysis and entropy to model this wider class of models allows greater flexibility in describing statistical classes.

Payoff: Complex phenomena such as feedback in coding can be modeled under dynamic heterogeneous conditions.

Network Channel Architecture
Feedback Channel & Geometric Invariants

Renyi Channel Correlation Analysis
(connected to geometric curvature)

- Maximal correlation, a measure of dependence:
  \[ \rho(X, Y) \triangleq \sup_{f(X), g(Y) : E[f] = E[g] = 0, E[f^2] = E[g^2] = 1} \frac{E[f(X)g(Y)]}{E[f^2]} \]

- Conditional Expectation Operator: \( B : \mathcal{F}_Y \mapsto \mathcal{F}_X \)
  \[ B(f) = E[f(X)|Y] \]

- Renyi
  \[ \rho(X, Y) = \sup_f \frac{E[(B^f B(f))^2]}{E[f^2]} \]
Feedback in Coding Theory

D. Tse, Berkeley, P. Gupta, Alcatel Lucent, D. Shah, MIT

Approach: Coding theory classically assumes fixed statistic and fixed methods of coding for a given set of network and interference conditions.

Payoff: Feedback in coding methods can significantly improve throughput under dynamic network and interference conditions.

Feedback Coding Approach

Areas Where Improves Performance (including side information)

\[ \bar{\alpha} := \frac{\bar{m}}{\bar{n}} \]

previous example

\[ \frac{1}{2} \quad \frac{2}{3} \quad 2 \]

\[ \alpha := \frac{m}{n} \]

\[ \frac{m}{n} = \frac{\log \text{INR}}{\log \text{SNR}} \]

INR = interference-to-noise ratio
Predict system performance using mathematical invariants from measured data

**Measured Performance Regions**

- **Deterministic Content**
- **Hybrid Content**
- **Random Content**

**Architectures**
- Deterministic
- Hybrid
- Random

**Protocols**
- Deterministic
- Hybrid
- Random

**Content**
- Deterministic
- Hybrid
- Random

**Architecture**
- Deterministic
- Hybrid
- Random

**System Measurements**

- **Network States** (packets, packet blocks, packet groups)
- **Software States** (variable, subroutine, program)
- **Hardware States** (register, ram, virt. mem)

**Properties**
- **Heterogeneous Information**
- **Deterministic Architecture**
- **Hybrid Architecture**
- **Random Architecture**

- **Global Properties**
  - Unstable/Un-resourced
  - Insecure

- **Statistical Properties**
  - Stable/Resourced
  - Secure

**Invariants Predict Performance**

- **Less**: Information Loss Under Disruption/Live
- **More**: Latency, Resource Intensive/Safe

- **Less**: Latency/Disruption Tolerant/Safe
- **More**: Controllable/Live

**Best Integrated Performance Region**
Hodge Theory for Invariants in Network Algorithms

ST Yau, Harvard, Ali Jadbabaie, UPenn, Fan Chung Graham, UCSD

Approach: Hodge decompositions allow natural functional invariants to be used on extremely complex structures

Payoff: Analysis of Hodge decomposition can be applied to whole classes of networks to characterize invariant parameters and predict performance.

Hodge Decomposition

Gives Powerful Functional Invariants

The $k$-Laplacian acting on $C^k(X)$ is defined by

$$\Delta_k = \partial_{k+1} \partial_{k+1}^* + \partial_k^* \partial_k$$

- $\Delta_k f = 0 \iff \partial_k f = 0$ and $\partial_{k+1}^* f = 0$
- $C^k(X) = \ker \Delta_k \oplus \text{Im}(\partial_{k+1}) \oplus \text{Im}(\partial_k^*)$ is an orthogonal decomposition called the Hodge decomposition.

Write $\chi_e = h_e + g_e + c_e$

- $g_e = \text{proj}_{\text{Im} \partial_1^*}(\chi_e)$: Gradient flow
- $c_e = \text{proj}_{\text{Im} \partial_2}(\chi_e)$: Curl flow
- $h_e = \text{proj}_{\ker \partial_1^* / \text{Im} \partial_1^*}(\chi_e)$: Harmonic flow

Invariant Analysis of Page Rank (Google)

PageRank

$$pr(\alpha, s) = \beta s D^{-1/2} G_{\beta} D^{1/2}, \quad \beta = \frac{\alpha}{1-\alpha}$$

Invariant Analysis of Google’s Page Rank Algorithm for Different Values of Beta
**Approach:** Dynamic measured data has correlated structures that are difficult to characterize by standard tools in algebraic topology such as homology. Additional features such as Conley index can augment invariants provided by algebraic topology.

**Payoff:** Dynamic modes of networks and networked systems can be captured by new methods in discrete Morse theory and algebraic topology to predict performance.

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**Dynamic Time Series**

Initial Time Series

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**Use of Conley Index Allows Verification of Dynamics for System Assurance**

Model Equivalence Checking

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**Time Series Data**

Graphs from Time Series

Graphs With Invariant Cycle

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**Bugs and System Instabilities Can Be Measured and Model Checked in Real Time**

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**Use of Conley Index Allows Verification of Dynamics for System Assurance**

```
Given \( f : X \rightarrow X \) and \( P_0 \subset P_1 \subset X \) need to compute

\( f_\ast : H_n([P_1]/[P_0],[|P_0|]) \rightarrow H_n([P_1]/[P_0],[|P_0|]) \)
```
Approach: Dynamic network information flow can be parameterized by its max flow min cut value relative to the network topology.

Payoff: Categories of flows can be developed using sheaf theoretic formulation for max-flow min-cut parameters to characterize and verify system performance.

Sheaf Formulation For Max Flow Min Cut and Network Code

\[
[0, \text{maxflow}] = \bigcup_{\text{flows}} [0, \text{flowval}] \\
= \text{im} \ (O\otimes F)_x \rightarrow (O\otimes F)_{pt} \\
= \text{im} \lim_{\text{cuts}} (O\otimes F)_{\text{cut}} \rightarrow (O\otimes F)_{pt} \\
= \lim_{\text{cuts}} \text{im}(O\otimes F)_{\text{cut}} \rightarrow (O\otimes F)_{pt} \\
= \lim_{\text{cuts}} [0, \text{cutval}] \\
[0, \text{mincut}] = \bigcap_{\text{cuts}} [0, \text{cutval}]
\]

Categorical Invariants For Coded Information Flows

Joint project with DARPA/DSO GRAPHS program
Complex Networks uses advanced mathematical analysis of information systems measurements to resource, verify, and secure distributed Air Force infrastructures

- Princeton MURI – dynamic analysis of packets for airborne network resource management
- Yale/Telcordia commercial grant – real time system security policy verification
- Columbia/MIT – information theory for new quantum semiconductors
Space and Airborne
Cognitive RF
Scott Erwin, AFRL/RV, John Matyjas, AFRL/RI, Vasu Chakravarthy, AFRL/RY

Approach: Use advanced non-parametric geometric measurement and game theoretic techniques with Generalized Likelihood ratio test to enable training on RF interference data in conjunction with advanced MIMO beam-forming techniques to remove interference

Payoff: AF will be able to conduct operations in crowded dynamic spectrum environment

Complex RF Environment

Improved Detection

Improved Throughput

Space Time Network

Adaptive Detection

Network Measurement & Invariants

Fig: The structure of the GLRT-EC detector.
Approach: Verification of classical vs. quantum states in a network provides a new class of measurement problems which need invariants for analysis of states of large scale quantum systems for information assurance, communication, and computing.

Payoff: Integrating new invariant network techniques with new quantum representations will allow a much more integrated way of analyzing large scale quantum network and computational systems.

Data from Quantum Network & System Measurements

Photonic Device Measurements

Optical Measurements

Representation of Quantum Logic

New MURI 2012: Measurement and Verification in Quantum Information Systems
Approach: Verification of classical and quantum states in a network and system provides a new class of measurement problems which need invariants such as computational homology for analysis of states.

Payoff: Integrating new invariant network techniques with new classical and quantum representations will allow a much more integrated way of analyzing & securing large scale networked and computational systems.

**Network Information**

**Properties Of Curvature**

**Classical Information**

Triangle Inequality

\[ D_{AB} + D_{BC} \geq D_{AC} \]

Polygonal Inequality

\[ D_{AB} + D_{BC} + \ldots + D_{YZ} \geq D_{AZ} \]

**Quantum Information**

Triangle, ..., Polygonal Inequalities are violated

\[ |\psi\rangle = (|\uparrow_1, \downarrow_2\rangle - |\downarrow_1, \uparrow_2\rangle)/\sqrt{2} \]

\[ \Rightarrow \exists \ no \ P(A_1, B_2, C_1) \]

**Network/System Decomposition**

2D Ricci flow

\[ \frac{1}{g_{ab}} \frac{dg_{ab}}{d\tau} = -2K \]
Complex Networks Invariants for Risk Assessment Measurement of Human vs. Machine Performance

*Leslie Blaha, AFRL/RH*

**Approach:** Complex Networks invariants can be used to assess risk on human vs. machine operation when faced with complex decision task.

**Payoff:** Detailed understanding and automation of how to trade human vs. machine performance in time critical functions such as cyber security, autonomous operation of air vehicles. 

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*Human Risk Lower*  
*Machine Learning Risk Lower* 

<table>
<thead>
<tr>
<th>t</th>
<th>Observed sequence</th>
<th>Hidden sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Walk</td>
<td>Sunny</td>
</tr>
<tr>
<td>2</td>
<td>Walk</td>
<td>Sunny</td>
</tr>
<tr>
<td>3</td>
<td>Shop</td>
<td>Rainy</td>
</tr>
<tr>
<td>4</td>
<td>Clean</td>
<td>Rainy</td>
</tr>
<tr>
<td>5</td>
<td>Shop</td>
<td>Rainy</td>
</tr>
<tr>
<td>6</td>
<td>Walk</td>
<td>Sunny</td>
</tr>
<tr>
<td>7</td>
<td>Clean</td>
<td>Sunny</td>
</tr>
</tbody>
</table>
Recent Program Awards

• **Dan Spielman**
  – MacArthur Genius Award (2012)

• **Ingrid Daubechies**
  – Fellow of the American Mathematical Society 2012
  – Benjamin Franklin Institute Medal, 2012
  – Leroy Steel Prize From American Mathematical Society 2012
  – IEEE Jack Kirby Signal Processing Medal 2011

• **Robert Calderbank**
  - IEEE/Hamming Medal Winner (2012)

• **Vincent Poor**
  - National Academy of Science (2011)

• **Emmanuel Candès:**
  – Collatz Prize (Mathematics), (ICIAM) (2011)
  – Winner, Sixth Vasil A. Popov Prize (Mathematics), (2010)

• **ST Yau**
  – Wolf Prize Mathematics, 2010

• **Joel Tropp:**
  – Eighth Monroe H. Martin Prize, 2011

• **Yonina Eldar**
  – IEEE Fellow 2013

• **Mung Chiang:**
  – IEEE Fellow 2012
  – IEEE Kiyo Tomiyasu Award in 2012

• **Junshan Zhang**
  – IEEE Fellow 2012
Academia/Commercial Outreach

• Keynote Lecture, American Society of Mechanical Engineers, Complex Systems 2012
• Keynote Lecture, International Conference on Complex Networks, 2012
• Keynote Lecture, IEEE, CogSima, 2013
• Invited Lecture, Yale Mathematics, Anniversary of Coifman, Jones, Rokhlin Achievements
• Organizer: London Institute of Mathematics: Mathematics of on Statistical Verification, March 2012
• Organizer, OSTP Meeting on Complex Engineered Systems, 2012
• Invited Speaker, Allerton, IEEE Conference on Information Theory, University of Illinois 2012
• Invited Speaker, IDGA Big Data, Federal Meeting Washington DC, 2013
• Invited Speaker, Neuro-Information Processing, Lake Tahoe, 2012
• Invited Speaker: Dagstuhl Germany, Mathematics of Information Flow, 2012
• Invited Speaker: USCD Information Theory and Applications, LaJolla 2013
Program Impact & Collaboration with Agencies

- **OSTP/NITRD – Co-Chair Large Scale Networks Working Group**
  - New national thrust – Complex Networks and Systems inspired by AFOSR program – Workshop “Complex Engineered Networks” organized by leader of AFOSR Complex Networks MURI “Information Dynamics in Networks”

- **ASDR&E**
  - Engineered Resilient Systems – Complex Networks and Foundations of Information Systems on Roadmap

- **DARPA Collaboration/joint program reviews**
  - Graphs – Mathematics of graphs and networks agent
  - Defense Science Office Mathematics Advisory Panel
  - InPho – Information in a photon/quantum network collaborative funding
  - Com-EX cognitive network program transition agent

- **IARPA – Quantum Computer Science Working Group**

- **ARL/ARO Network Science Board of Advisors**

- **NSF Future Internet, Cyber Physical Systems**
Complex Networks Trends

• Local Network Theory
  – Geometric and binary information coding
  – Coding information with network performance objectives
  – Integration with verification and quantum methods

• Network Management
  – Nonparametric strategies for assessing network performance
  – Distributed strategies for measuring and assessing network information transfer
  – Sparse network management

• Global Network Theory
  – Geometric flow analysis for prediction and management of network performance
  – Global state space taxonomy and categorization

• Information Systems Research
  - Combined network, software, and hardware analysis
  - Defining correct input data for given mathematical assessment
  - Invariant metrics for analysis of network performance

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Other Program Interactions

**Cyber Operations**: Joint University Center of Excellence: “Cyber Vision 2025” – Enabling Technologies workshops “Secure Cloud Computing” with university and AFRL/RI

**Dynamics and Control**: Verification and Validation of Complex Systems

**Physics and Materials**: New Joint MURI Topic: “Large Scale Integrated Hybrid Nanophotonics”

**Socio-Cultural Analysis**: Social Networks – Joint MURI Topic: “Stable Metrics for Inference in Social Networks” – UCLA/USC/ASU

**Quantum**: Interaction with quantum network and quantum estimation processes through lab tasks
- Joint EOARD initiative at Cambridge

**Information Fusion**: Critical feature selection in sensor networks

**Optimization**: Competing optimization requirements.

**Decision**: Networks of neurons.

**Biology**: Systems biological processes as networks.
Transition Activities

• AFRL
  – AFRL/RI/RY – DARPA InPho program/DARPA Graphs program
  – AFRL/RI/RY/RV – distributed secure space communications
  – AFRL/RW/RV/RH – verification and validation of complex systems

• STTR
  – Intelligent Automation: Transition to ESC of Airborne Networks management – transition to Boeing for test-bed
  – Avirtek: Secure router application interface- AFRL/RI
  – Andro – Joint Spectrum Center Lockheed transition of automated spectrum management tool
Transition Activities

- **Customer/Industry**
  - Collaboration with ACC/GCIC, Air Force Spectrum Management Agency on JALIN ICD
  - Collaboration with Boeing, ESC, IAI for transition of coding and routing management protocols baseline CORE tools to Rome Lab for possible integration in CABLE JCTD
  - Briefing to Space Command/Peterson for potential collaboration
  - Interaction with Northrop Grumman/BACN airborne networking program for potential collaboration
- **OSD**
  - Complex Systems Engineering and Systems 20/20 initiative
  - Software Assurance and Security Initiative
  - Robust Command and Control Initiative
- **Commercial**
  - Interaction with Stanford on real time network information recovery
  - New initiatives with Akamai for content distribution analysis
  - Interaction with USFA/DHS/CISCO on router algorithm design